Alveolar ridge alterations in the maxillary anterior region after tooth extraction through orthodontic forced eruption for implant site development: a clinical CBCT study

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Abstract: Objective: To investigate the effects of orthodontic forced eruption (OFE) with the straight-wire appliance in the dimensions of the alveolar process when used for extracting compromised maxillary anterior teeth and implant site development. Material and methods: Cone-beam computed tomography (CBCT) scans of 7 patients needing extraction of 17 maxillary anterior teeth were obtained before and immediately after OFE. Alveolar plate height and thickness measurements were performed on the buccal and palatal socket walls in CBCT sagittal cross sections. Statistical analysis included sample size calculation, paired t-test, and Wilcoxon test to evaluate alveolar plate dimensional changes and linear regression analysis to assess whether bone changes and the feasibility of implant insertion were associated to tooth type and root length, baseline alveolar plate thickness, and age. Results: OFE caused statistically significant reduction of the buccal alveolar plate height (1.95 ± 1.83 mm) and significant increase of the palatal alveolar plate height (1.31 ± 2.41 mm) in the central tooth socket areas. Buccal reduction was associated positively to the baseline root length and negatively to the thickness of the corresponding plate in the apical level. A non-significant increase was noted in both buccal (0.23 ± 0.93 mm) and palatal (0.63 ± 1.59 mm) proximal bone. Inadequate buccal bone support hindered immediate implant placement in six sockets; however, all inserted implants showed adequate and gradually increasing stability from insertion to final restoration. Conclusions: OFE resulted in favourable increase in the heights of the palatal and proximal alveolar bone and significant reduction in the buccal plate height, which inhibited implant placement in 35% of the treated sockets.

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Title Page

Alveolar ridge alterations in the maxillary anterior region after tooth extraction through orthodontic forced eruption for implant site development: A clinical CBCT study

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Summary

Objective: To investigate the effects of orthodontic forced eruption (OFE) with the straight-wire appliance in the dimensions of the alveolar process when used for extracting hopeless maxillary anterior teeth and implant site development.

Material and Methods: Cone-Beam Computed Tomography (CBCT) scans of seven patients needing extraction of 17 maxillary anterior teeth were obtained before and immediately after OFE. Alveolar plate height and thickness measurements were performed on the buccal and palatal socket walls in CBCT sagittal cross-sections. Statistical analysis included sample size calculation, paired t-test and Wilcoxon test to evaluate alveolar plate dimensional changes and linear regression analysis to assess whether bone changes and the feasibility of implant insertion were associated to tooth type and root length, baseline alveolar plate thickness and age.

Results: OFE caused statistically significant reduction of the buccal alveolar plate height (1,95±1,83mm) and significant increase of the palatal alveolar plate height (1,31±2,41mm) in the central tooth socket areas. Buccal reduction was associated positively to the baseline root length and negatively to the thickness of the corresponding plate in the apical level. A non significant increase was noted in both buccal (0,23±0,93mm) and palatal (0,63±1,59mm) proximal bone. Inadequate buccal bone support hindered immediate implant placement in six sockets; however, all inserted implants showed adequate and gradually increasing stability from insertion to final restoration.

Conclusions: OFE resulted in favorable increase in the heights of the palatal and proximal alveolar bone and significant reduction in the buccal plate height, which inhibited implant placement in 35% of the treated sockets.

Key words: orthodontic forced eruption, alveolar ridge, alveolar process, anterior maxilla, immediate implants, implant stability

Introduction

The alveolar process develops and is highly dependent on the eruption and presence of teeth.[1,2] The sequence of post-extraction alveolar changes and the histologic pattern of tissue remodelling have been investigated extensively in animal models. The crestal region of the buccal and lingual bone wall, comprised solely of bundle bone, has been shown to exhibit pronounced vertical resorption, especially on the buccal side, in the first 8 weeks post-extraction. Socket fill with woven and later with lamellar bone is accompanied by resorption of the outer surfaces of both bone walls[3,4] with marked reduction in the vertical and horizontal dimensions and the overall size of the alveolar process irrespective of flap elevation or flapless technique used for tooth removal.[5,6] Postextraction dimensional changes of the anterior maxilla involve asymmetrically greater resorption of the buccal surfaces than the palatal,[7] resulting in a distinct shift of the center of the upper edentulous ridge towards the palate.[8]

Various methods have been used to evaluate bone remodelling after single tooth extractions. Covani *et al.* 2011[9] Showed that single tooth extractions in posterior teeth caused significant changes in the buccal wall with the alveolar crest shifting in a lingual/palatal direction and the bone loss being double at the midpoint of the socket compared to the distal and mesial points. Mesiodistal analysis of alveolar ridge changes with standardised intraoral X-rays showed a 4.16mm height loss in single- and 4.48mm in multi-root teeth after 3 months of healing in the mid-socket area. This vertical loss followed similar pattern in all sockets and predisposed any future implants placed in fresh extraction sockets to possible thread exposure.[10]

Currently, cone beam computed tomography (CBCT) has facilitated the three-dimensional (3D) quantification of post-extraction ridge alterations in the maxillary esthetic zone. Acquisition of CBCT cross-sectional views prior to and one year post extraction has disclosed that maxillary premolar and incisor single tooth removal results in marked alveolar hard tissue reduction not only in the marginal portion but also in more apical levels.[11] Chappuis *et al.* 2013[12] showed that CBCTs in the anterior maxilla depicted a vertical ridge loss 3.5 times greater than that reported with other methods and subjects with thin-wall phenotypes presented significantly greater vertical bone resorption.[12]

Alveolar ridge bone preservation procedures are regularly performed to prevent or minimise post-extraction alveolar shrinkage. Placement and incorporation of a widely used xenograft (Bio-Oss® Collagen) into extraction sockets involves a series of tissue events. Histologic biopsies have demonstrated that after 4 weeks of healing the main tissue constituents were 45% newly formed bone and 37% connective tissue while the graft particles served as scaffold for new bone formation.[13] Even though marked reduction through contraction of the marginal surface area was avoided after 3-6 months of xenograft healing, grafting procedures failed to prevent resorption of the alveolar crest while large numbers of Bio-Oss particles were still present.[14,15] Using the same xenograft for over-augmentation of the buccal bone in conjunction with socket fill failed to compensate for post-extraction changes.[16] Autologous bone grafts, which are considered the gold standard in bone defect repair,[17] could not prevent ridge resorption after tooth extraction.[18] Clinical studies evaluated the effectiveness of bone augmentation procedures, with or without barrier membranes, in post-extraction alveolar ridge preservation; however, their systematic assessment concluded that the amount of evidence, especially in the anterior maxillary area, is sparse. Even though socket preservation procedures could possibly lessen vertical and horizontal contraction, they did not manage to totally prevent alveolar resorption at the grafted sites and recommendations regarding the ideal type of biomaterial or surgical technique could not be robustly supported.[19-20]

Immediate implant placement provides reduced overall treatment time and has also been considered as an alternative to prevent post-extraction alveolar ridge contraction. Studies in the canine animal model have provided evidence that when implants are inserted immediately after tooth extraction successful osseointegration is accompanied by major reduction in the height and width of the buccal bone after 12 weeks of healing[21,22,23] and the diminution of alveolar ridge dimensions could not be prevented.[22-24] Immediate implants when placed in fresh human extraction sockets have exhibited high survival rates;[25] however, in the maxillary anterior region, variable esthetic outcomes and gingival midfacial recessions were noted in cases with non-detectable buccal bone walls on CBCTs.[26] Guided tissue regeneration procedures when applied simultaneously to immediate implantation did not seem to prevent alveolar ridge resorption.[27]

Orthodontic forced eruption (OFE) has been proposed initially as a method to resolve infrabony periodontal defects[28] and assist in crown lengthening of traumatised and/or non restorable teeth.[29] The method was further applied as a non invasive alternative for implant site development in the anterior maxilla. Alveolar ridge preservation and reconstruction were advocated to be feasible in a more predictable and conservative manner prior to implant insertion.[30,31] The process described in the available literature involves the placement of orthodontic fixed appliances that facilitate gradual extrusion and final extraction of hopeless teeth. Simultaneously, augmentation of both hard and soft tissues has been proposed through coronal relocation of the alveolar crest and gingival margins in the corresponding sites.[30,32] Nonetheless, the available literature on the efficacy of OFE by using the tooth periodontal ligament apparatus of hopeless teeth for enhancing alveolar reconstruction and new bone formation is mainly derived from case reports,[33] while the biomechanical considerations of orthodontic tooth movement regarding the magnitude and direction of forces are not yet clarified.

Hence, the primary outcome of this study was to assess by using CBCTs the pattern of alveolar ridge remodelling in the anterior maxillary region following tooth extraction with OFE. Secondary outcomes included the efficacy of immediate implant insertion in the treated sockets and their subsequent stability. In addition, it was evaluated whether alveolar crest height changes and implant placement were associated with the tooth type and root length, the baseline thickness of the buccal and palatal alveolar walls of the corresponding sockets and patient age.

Reporting follows the STROBE guidelines checklist for prospective observational studies.

Materials and Methods

Data collection

The research protocol of this observational study was approved by the Ethics Committee of School of Dentistry, …….. University as being in accordance with the Helsinki Declaration II (Approval Reference No.: 303). Adult patients presented to the Department of .... for treatment of anterior maxillary, non restorable teeth with implant restorations were invited to participate in the study and screened for being suitable.

Inclusion criteria required age greater than 18 years, non restorable and in need of maxillary anterior teeth (only central incisors, lateral incisors and canines) extractions, of minimum 4mm bone support, intact buccal and palatal alveolar bone plates evident on initial CBCT, no previous orthodontic treatment, and non smokers. Patients with the following characteristics were excluded from selection: smoking (current or for the past 5 years), alcohol or other substance abuse, bone metabolic disease or medication affecting bone metabolism, other systemic disease (diabetes, autoimmune disease), medical history of malignancy, radiotherapy, chemotherapy, periapical pathology, active periodontal disease and inadequate oral hygiene. All patients who fulfilled the above criteria were given thorough explanation of the study protocol, treatment stages, possible advantages or ineffectiveness and complications of the procedures. Written informed consent was obtained.

CBCT acquisition and image reconstruction

CBCT scans were obtained with the NewTom VGI (Cone Beam 3D Imaging, Verona, Italy) imaging system. Initial CBCT was taken before the start of any type of treatment and final CBCT was taken 4 weeks after the completion of OFE and immediately prior to implant placement. It is a common practice in implant surgery to perform an initial CBCT at baseline for patient evaluation and initial consultation and then a second one after tooth extraction or guided bone regeneration (GBR) and augmentation procedures.[11,12,19,20] This allows accurate representation of changes induced by any intervention since initial consultation (extractions, GBR) for assessing whether favourable conditions exist for implant placement and also decide the size and type of implants or construct surgical guides; thus, the radiation dose could be justified and the ALARA prinsciple was followed.

Each patient was examined in an upright, standardised position using a beam of light. The horizontal reference beam coincided with the Frankfort horizontal plane (a line defined by the superior border of the external auditory meatus and the infraorbital rim) set parallel to the floor and the vertical reference beam coincided with facial midline. Ideal head position was followed by fixing the head to the scanners hard frame so as to maintain stability during the scanning procedure. Scanner settings were at 110 kV, 1.71-7.60 5mA, exposure time 3.6 secs, field of view (FOV) of 12cm, voxel size 0.15mm, signal greyscale 12 bit, and slice thickness 1mm. The CBCT data were saved as Digital Imaging and Communications in Medicine (DICOM) files and 3D reconstructions were attained with the NNT Viewer software (Cone Beam 3D Imaging, Verona, Italy). Further standardization was determined by head re-orientation on the software. On the lateral view, the Frankfurt horizontal plane, passing from each subject's right porion and right orbitale points, was set parallel to the software's horizontal reference line. On the coronal view, the plane passing through crista galli was set parallel to the software's vertical reference line.[34,35] In this way any pitch, roll and/or yaw discrepancies during CBCT exposure were adjusted; hence, all sagittal cross-sectional slices and images were acquired on this software re-oriented and standardised head position.

Intervention

<u>Orthodontic procedures</u>

Pre-adjusted, conventional orthodontic fixed appliances (Roth prescription used for all teeth but canines, which were bonded with standard edgewise brackets with 0° tip and torque, 0.022inch slot) were bonded on the buccal surfaces of the maxillary dental arch. Prior to the initiation of OFE, complete levelling and alignment of the dentition was performed with NiTi wires. Adjustments were scheduled every 4 weeks for sequentially increasing the cross-sectional size of the wires. Then, gradual extrusion of the corresponding teeth was achieved by rebonding their brackets in a more gingival position and refitting the working orthodontic wires (0.017x0.025 inch NiTi) inside the bracket slots as per the straight-wire technique for orthodontic extrusion.[36] Rebonding was performed at a crown level that optimal extrusion forces of 10-15gr per tooth could be delivered. Extrusive forces were measured with a gauge (Dentaurum, Ispringen, Germany). Reduction of the incisal and palatal tooth surfaces was performed in order to avoid premature contacts and traumatic occlusion on each re-activation appointment. Endodontic treatment had already been performed 4-8 weeks before initiation of orthodontic treatment to refrain patients from pulp sensitivity due to the enamel reduction. Upon completion of OFE, orthodontic appliances were left *in situ* for 4 weeks to allow maturation of the newly formed bone.

<u>Surgical procedures</u>

Comprehensive clinical examination was performed 4 weeks after completion of OFE accompanied with radiographic acquisition of the final CBCT scan. One hour preoperatively, patients were advised to initiate prophylactic antibiotic and analgesic therapy (Amoxicillin 500mg and Paracetamol 1000mg). Oral disinfection was performed with 0.2% chlorhexidine digluconate mouthwash (Corsodyl®, GlaxoSmithKline, Brentford, UK). Tooth extraction was performed with minor incision of the circumferential periodontal ligament fibers as there was no bone support. Immediate implant placement (NanoTite™, Certain® PREVAIL®, Biomet 3i™, Palm Beach Gardens, Florida, USA) was performed with the flapless technique by using the palatal bone as a guide for pre-drilling (Figure 1). All implants were of 13mm length and 4mm diameter in central incisor and canine sites and of 3.25mm diameter in lateral incisor sites. Torque for implant insertion was set on 35Ncm. Implant stability was measured with Resonance Frequency Analysis (RFA) after attaching the appropriate Smartpeg™ on the implant neck and Implant Stability Quotient (ISQ) was recorded with the Osstell™ Mentor device (Integration Diagnostics AB, Göteborg, Sweden). ISQ was measured both on the mesio-distal and the bucco-lingual direction as per the manufacturer's instructions immediately after implant placement, on provisonalisation and at final prosthetic restoration.

<u>Provisionalisation and final prosthetic restoration</u>

Monophase Polyether impressions were taken immediately after implant placement (Impregum™ Soft Polyether Impression Material, 3M ESPE, St. Paul, MN, USA) and provisional restorations free of contacts in all movements were delivered to the patients within 24-48 hours post-surgery. Metal-ceramic final prosthetic restorations were inserted 6 months after implant placement.

CBCT measurements

Each socket unit was extending from the mesial to the distal side of the corresponding tooth of interest and was further divided into the central socket and the proximal bone, which were the sites mesial and distal to the central socket. The central socket was comprised by the most mid-socket CBCT slice, which corresponded to and included the longest part of the tooth root (absolute central slice), and the two slices extending 1mm mesial and distal to this absolute central slice. The slices extending further to the mesial and distal of the central socket until the contact points with the neighbouring teeth were the proximal sites. The cross-section images were imported into the image processing software ImageJ (1.42q; Wayne Rasband, National Institutes of Health, Bethesda, MA, USA). In order to have standardized and reproducible between the initial and the final CBCTs reference lines, which would also be unaffected by the presence or albescence of teeth and the alveolar process's angulations and anatomy, a main horizontal reference line (HRL palate) was drawn as the tangent to the deepest part of the palate on every sagittal cross-section (Figure 1). Parallel to this main horizontal reference line, three additional reference lines were drawn passing from the root apex (HRL Apex), the tip of the buccal alveolar crest (HRL Buccal crest) and the tip of the palatal alveolar crest (HRL Palatal crest) in the initial CBCT images while the final CBCT images did not require the horizontal reference line passing from the root apex (Figure 2a and Figure 2c).

The following measurements (Figure 2) were performed at right angles by single calibrated and experienced examiner (...) with ImageJ on all cross-sections extending throughout the anatomic areas (socket units) of interest:

- Buccal bone plate height (bh): tip of the buccal alveolar crest (HRL Buccal crest) to the main horizontal reference line (HRL palate) on initial and final CBCTs
- Palatal bone plate height (ph): tip of the palatal alveolar crest (HRL Palatal crest) to the main horizontal reference line (HRL palate) on initial and final CBCTs
- Buccal root length (brl): tip of the buccal alveolar crest (HRL Buccal crest) to the root apex (HRL Apex) only on initial CBCTs (central slices)

- Palatal root length (prl): tip of the palatal alveolar crest (HRL Palatal crest) to the root apex (HRL Apex) only on initial CBCTs (central slices)

After measuring the root length on both buccal and palatal sides each distance was divided in half and the middle point served also as a reference for performing alveolar bone plate thickness measurements on lines parallel to the main horizontal reference line (HRL palate).

Alveolar thickness was measured at three different heights in the central socket areas as follows (Figure 1b):

- Buccal plate cervical (bpc): at a distance 1mm from the tip of the buccal crest
- Buccal plate middle (bpm): at the level of the middle of buccal root length (brl)
- Buccal plate apical (bpa): at the level of the root apex
- Palatal plate cervical (ppc): at a distance 1mm from the tip of the palatal crest
- Palatal plate middle (ppm): at the level of the middle of palatal root length (prl)
- Palatal plate apical (ppa): at the level of the root apex

Sample size

Taking into account that tooth extraction results in a mean diminution of 2mm on the buccal alveolar height,[11,37] it was considered that a mean difference of 2mm with a standard deviation of ±1.5mm of the mean differences in alveolar height gain or loss through OFE is a meaningful clinical important effect. With *a* set at 0.05 and a power of 80% it was calculated with G* Power software (http://www.gpower.hhu.de/en.html) that 10 sockets were required to reveal statistically significant differences due to the applied treatment in the bone height of esthetically critical areas.[38] For accounting any possible problems that could have arisen during patient follow-up related to orthodontic fixed appliance tolerance or decisions to drop-out from the research, 17 eligible sockets were included in the present study.

Statistical methods

Data analysis was performed using each socket as the experimental unit. Descriptive statistics for all parameters with mean values and standard deviations were calculated. The alveolar ridge height changes over time, between baseline and at the end of OFE, were examined with paired *t*-test (parametric) or Wilcoxon test (non-parametric) according to the normality of data distribution. Linear regression analysis taking into account the clustering within patients was used in order to identify any associations between alveolar bone height changes and the feasibility to perform immediate implant insertion post-OFE with the tooth type, root length, baseline alveolar plate thickness and patient age. Analysis of variance (ANOVA) was used to assess implant stability changes between implant insertion, provisionalisation and final prosthetic restoration. A two-sided 0.05 alpha level was set to define statistical significance. Reliability was calculated with the intra-class correlation coefficient and systemic error was assessed using paired *t*-test by remeasuring of 20% of the slices after 2 weeks. All analyses were done in Stata SE 14.2 (StataCorp., College Station, TX, USA) and the dataset was openly provided (http://doi.org/10.5281/zenodo.2565025).

Results

Participants

All patients who had accepted to participate in the study concluded the orthodontic treatment with the extraction of the relevant teeth through the application of OFE with no missing data. From the 17 treated sockets only 11 exhibited adequate amount of supporting bone for immediate implant placement. Patient demographics (age, gender), total number and localisation of teeth extracted with OFE, aetiology of tooth loss, number and sites eligible for immediate implant placement on each patient and duration of orthodontic treatment are presented in Supplementary Table 1.

Outcome data

A total of 230 images (102 from the central socket areas and 128 from the proximal areas) were acquired and measured in the sagittal CBCT cross-sectional slices. On each time point, 51 images were from the central socket areas and 64 images were from the proximal areas. According to the Shapiro-Wilk test, data of all variables showed normal distribution.

<u>Baseline root length and alveolar thickness.</u> At baseline, root length as measured in the absolute central slice of each socket was 5.26±2.05mm on the buccal and 6.91±2.24mm on the palatal, with the palatal root length being significantly greater than the buccal (P<0.001 < 0.05).

The thickness of the alveolar buccal bone was 1,06±0.58mm, 1,24±0.85mm and 1,34±0.60mm measured at the cervical, middle and apical levels of the roots. The corresponding values for the thickness of the alveolar palatal bone were 1,61±0.56mm, 3,50±1.44mm and 6,15±2.72mm respectively (Supplementary

Table 2). Paired t-test comparisons showed that the palatal alveolar plate thickness was significantly greater from the buccal at all levels (cervical $P=0.01 < 0.05$, middle $P<0.001 < 0.05$ and apical $P<0.001 < 0.05$).

Alveolar ridge height dimensions and changes due to OFE. In the central areas of the sockets, buccal alveolar ridge height significantly reduced ($P<0.001$) 1.95±1.83mm as the initial mean value was 10.85±2.48mm and the final was 8.91±2.92mm. Alveolar ridge height significantly increased ($P=0.039<0.05$) 1.31±2.41mm on the palatal side with the initial mean values being 12.49±2.48mm and the finals 13.80±2.16mm. In the proximal sites, increases were noted on both buccal (0.23±0.93mm, $P=0.325$) and palatal (0.63±1.59mm, $P=0.121$) sides of the alveolar bone but did not reach statistical significance (Table 1, Figure 3).

Linear regression analysis showed significant and positive association of buccal alveolar height reduction in the central areas of the sockets with both the buccal and palatal root length of the extracted teeth, while the association was negative to the baseline buccal plate thickness in the apical third (Table 2).

Implant insertion and stability. Out of the 17 treated sockets only 11 (65%) showed favourable anatomy and adequate bone that facilitated immediate implant placement, which was performed without any additional grafting procedures. The ability to insert an implant after OFE was positively associated with the baseline buccal plate thickness at the cervical part of the socket (Table 3). ISQ values were 71±2.80 at implant insertion and 69.95±3.00 at provisionalisation showing a minor and non-significant decrease. When final prosthesis was inserted after 6 months, ISQ vales accounted for 74.45±2.97 and were significantly greater to the initial and the values measured at provisionalisation (Table 4).

Method error. Intraclass correlation coefficient (ICC) ranged between 0.992-0.999, indicating strong reliability. Paired t-test of repeated measurements ranged between -0.194mm to 0.01529mm, which was not significant (Supplementary Table 3).

Adverse events

The significant reduction of the buccal alveolar bone did not result in favourable implant site development and prohibited implant insertion in six (35%) of the OFE treated sockets. Inadequate bone dimensions of four sockets (two sockets on two different patients) were compensated by altering the prosthetic design of the final restorations with using either neighbouring implants and/or neighbouring natural teeth as abutments. Similarly, another patient did not receive implants in the two OFE treated central incisors' sockets due to extensive destruction and loss of the buccal alveolar plate. This was decided on the basis of compromised long term peri-implant esthetics due to the inadequate buccal bone support and the patient's decision to reject the option of additional bone grafting procedures. In this case, conventional prosthetic treatment included a fixed partial denture. The excessive resorption of buccal bone led us in the decision to stop recruiting more patients[39] for further testing the orthodontic treatment procedure the way it was described above , which is the method proposed in all available case reports, due to ethical reasons for not harming more patients. This adverse event kept our sample small.

Discussion

This prospective, observational clinical trial is the first using CBCT to evaluate the dimensional alterations in the anterior maxillary alveolar ridge after tooth extraction with orthodontic forces (OFE) delivered with the method proposed in the current literature, which is the straight-wire appliance. In the present study, quantitative evaluation of the sagittal CBCT cross-sections was used, which is a common practice in implant surgery for the evaluation of the anatomy and dimension of the alveolar process at baseline and after tooth extractions or any augmentation methods prior to implant placement.[11,12,19,20] Tooth extractions with OFE significantly decreased the buccal alveolar bone height in such a way that in some cases did not allow implant placement. Tooth extractions result in horizontal loss of 3.74±0.23 mm (26-63%) and vertical loss of 1.24±0.11mm (11-22%) at 6-7 months presented as weighted means over time in a meta-analysis of human studies.[40] In the present study, the mean buccal bone loss that occurred with OFE was slightly greater compared to simple extractions; however the significant gain in palatal bone and minor augmentation in proximal bone differs to the resorptive tissue reactions in all socket bone walls after simple extractions.

Contrary to the evidence of the present study, the effectiveness of OFE as a means for implant site development has been presented in the form of case reports with a general consensus that the method can result in favourable hard and soft tissue regeneration and can serve as a unique treatment option for implant site development in highly demanding cases regarding esthetics.[32,41-43] Nevertheless, the validity of the existing case reports could be questioned since bone response was either not rigorously evaluated or was based on 2-dimensional intraoral radiographs, which hinder the appropriate visualisation of the critically important buccal bone. By utilising CBCT as the assessment method in the present investigation, it was feasible to view and quantify in detail any changes in alveolar socket hard tissues.

Linear regression analysis revealed a positive association between the reduction of buccal alveolar height in the central socket areas with both the buccal and palatal root length meaning that the greater the root length the more pronounced the reduction of buccal bone was due to treatment. In addition, negative association was noted between buccal bone loss in the central socket areas and baseline thickness in the apical level showing that the thicker the alveolar plate was at the apex the less bone reduction was observed.

As far as the application of orthodontic forces is concerned, it has been found that pressure and tension areas are developed within the periodontal ligament resulting in a cascade of cellular and molecular interactions that finally lead to bone resorption and bone apposition in the respective sites.[44,45] The areas subjected either to pressure or tension and the resultant type of tooth movement are determined by the point of force application in relation to the center of resistance (CR) of a tooth. When a force (F) passes through the center of resistance, the result is bodily movement in the direction of the sense of the force whereas if the force is applied on a distance from the center of resistance, the result is tooth tipping due to the moment (M) developed. The magnitude of the moment is calculated by multiplying the force (F) times the perpendicular distance (d) between the point of force application and the CR, on lines parallel to the direction of the force.[46, 47] Bone response of the present study is in accordance to the biologic and biomechanical basis of orthodontic tooth movement. After the application of extrusive forces from the buccal surface and at a distance from the tooth's CR, the developed moment renders the buccal bone a recipient of compression while the palatal bone receives tension stimulation (Figure 4). Gradual extrusion and final extraction of teeth with the use of OFE and the straight-wire appliance follows the above biomechanical rules. Additional buccal root torque as proposed in the literature[33] to increase the buccolingual bulk of alveolar bone would thus be contraindicated as such forces would cause even more deleterious effects and further resorb of the critical for implant insertion cortical buccal bone.

Labial bone thickness measurements in the anterior maxilla have shown that 80% of anterior teeth exhibit less than 1mm of bone coverage. Almost 25-50% of the sites had even less than 0.5mm of buccal alveolar bone while only 1% of the incisors showed 1-2mm of labial bone thickness.[48-50] Contrary to the above studies; in the present study the thickness of the buccal bone was greater. This could possibly be attributed to our small sample size and the increased percentage of tooth loss due to periodontitis meaning that the crest was located more apically and hence closer to the thicker part of the anatomic base of the alveolar process. In addition, we used initial root length and its halves as a reference for measuring alveolar plate thickness and not standardised mm distances from the tip of the alveolar crest. With this measuring system, socket thickness measurements were not subject to metric mm distances apical to the crest tips but directly related to the corresponding roots in an individualised manner. In this way, direct associations between alveolar bone height changes and the initial buccal and palatal thickness of each socket for each included root length could be inferred.

Osseintegrated implants used for tooth replacement in partially or fully edentulous patients are a well established treatment.[51,52] Successful osseointegration though is not the only factor that defines implant success and in highly demanding esthetic areas, such as the anterior maxilla, the adequacy and stability of soft tissues and the underlying support from the marginal bone are of primary importance for achieving and maintaining pleasing outcomes in the long-term.[53] Esthetic evaluation of immediate anterior implants 1-year post-insertion has shown greater than 1.5mm facial gingival recession in the presence of facial osseous defects. The use of grafting materials and barrier membranes was ineffective to inhibit unfavourable tissue response dictating that insufficient amount and quality of peri-implant bone can result in deleterious long term esthetic outcomes. [54] Buccal bone dehiscence defect repair at extraction sites is greatly dependent on the defect size mesiodistally and the adequacy of proximal bone volume. Thus, the presence of large dehiscences with reduced amount of interdental bone results in compromised repair even with the use of guided tissue regeneration techniques. [55] Despite the minimal and variable response of proximal bone to OFE as reported in the present study, this response was in general positive and may serve as means to preserve bone and subsequently soft tissue support; however, long term evaluation is required.

Facial bone thickness of 2mm has been set as a criterion for achieving minimal peri-implant hard tissue loss.[56] The significance of adequate buccal bone was further substantiated by a post-healing height reduction of 1.2±2.1mm in cases of immediate implants when the baseline thickness was ≤1mm while cases with >1mm buccal bone exhibited only 0.4±1.3mm of alveolar crest height loss.[57] Huynh-Ba *et al.* 2010[58] also found that only a limited number of sites fulfilled the above requirement whilst most of the extraction sites exhibited thin (≤1mm) buccal bone. In the present study, the only factor affecting implant insertion was the baseline thickness of buccal bone at the cervical part of the socket. This finding corroborates with other studies that pertain the adequacy of buccal bone as a determining factor for implants in the anterior maxilla. Another significant finding of our study was that only 65% of the OFE treated sockets could receive implants. This percentage is lower compared to 79.2% of the sockets being eligible to receive implants after simple extractions and 90.1% of those treated with alveolar ridge preservation procedures;[59] however, there is no clinical trial directly comparing the efficacy between OFE and other bone grafting procedures in the anterior maxilla for implant site development and in the absence of evidence neither method can be advocated as superior.[60]

All OFE treated sockets in the present study were filled with newly formed bone and horizontal or vertical gaps were absent between the implant neck and the surrounding bone. This was also reflected in the high insertion torque, which was at least 35Ncm for all implants, and the resultant ISQ stability values. Primary stability of implants has been correlated to implant design, bone density and the alveolar morphology with dense bone exhibiting higher ISQ values.[61] Insertion torque values of 25Ncm are considered acceptable for immediate implants in the anterior maxilla and values ≥32Ncm are deemed as more favourable for achieving long term success rates.[62] As recent evidence identifies predictive correlations between bone grafting and lower ISQ values,[63,64] likewise the ISQ outcomes of the present study corroborate that OFE ensured such a bone response within the socket that allowed immediate implantation and provisionalization under conditions that favour implant stability.

Limitations of the present study include lack of controls, such as untreated sockets or sockets treated with another augmentation procedure. The ideal controls would have been untreated sockets; however, exposure to CBCT radiation without any benefit for patients was not performed for ethical reasons. Another type of comparison could be bone grafting or immediate implantation in a split-mouth design; hence not all patients who agreed to participate in the study needed more than one maxillary anterior implant. Another confounding factor was the great range in patients' age. Even though none of the patients had any general medical conditions that could predispose normal healing, it is well accepted that bone metabolism changes during ageing and is greatly dependent on hormonal factors. In addition, most of the teeth included in the study were considered hopeless due to periodontal disease. Apart from statistical analysis and the associations found, qualitative evaluation showed that central incisors with longer roots that were extracted due to trauma showed the greatest amount of buccal bone loss. The co-ordinate system used and the measurements made at right angles to the HRL indicate that the true changes in height may be actually greater as the reported values are a projection of the actual dimensions in the y axis. It was decided though to use this measuring system as this was independent to the presence or absence of teeth and the anatomic variability at the contours of the alveolar process between patients. Direct comparison with other studies should also be with prudence as the assessed variables and methods of measurement differ. The results of the present study generally apply when extrusive forces are delivered at a distance from the CR of treated teeth using conventional fixed orthodontic appliances and the straight-wire technique. Future studies may focus on the standardisation of CBCT measurements and the development of more favourable orthodontic biomechanical systems. In this context, ideal force systems regarding force magnitude and direction could achieve orthodontic extrusion without putting the burden of pressure on the thin buccal alveolar plate. Consequently, favourable tissue remodelling and implant site development could be generated through orthodontic bioengineering and elimination of extensive surgical procedures for alveolar reconstruction.

Supplementary material

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Conflict of interest

The authors have stated explicitly that there are no conflicts of interest in connection with this article.

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Figure legends

Figure 1. Illustration of implant site preparation with the flapless technique by using the palatal bone walls as a guide for pre-drilling. Implant insertion, final implant position and connection of the healing cups.

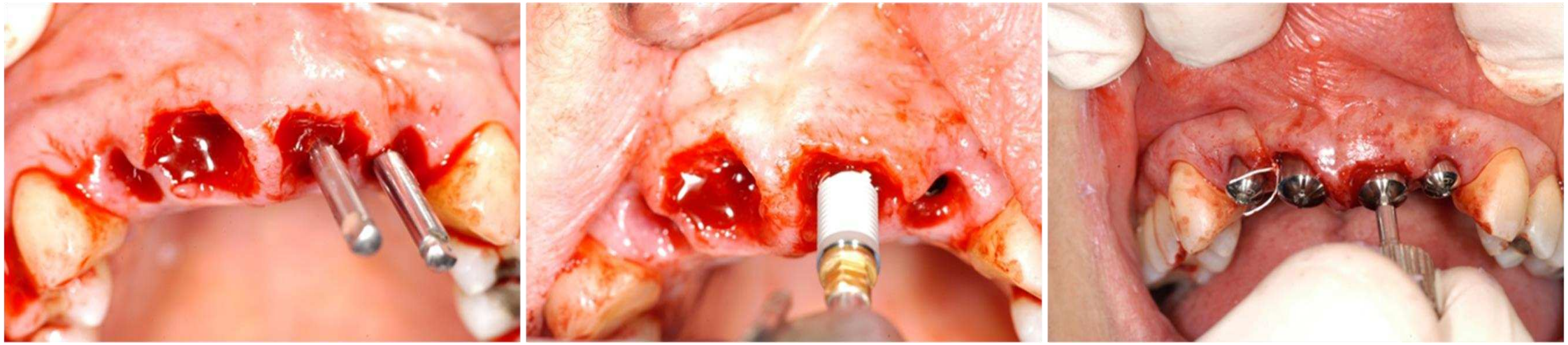


Figure 2. Reference lines and measurements performed on the initial (a and b) and final (c) Cone Beam Computed Tomoraphy (CBCT) sagittal cross sectional reconstructions. a. Alveolar ridge height and root length measurements performed at right angles to the HRL: horizontal reference line, which was drawn tangent to the deepest part of the palate at each slice. bh: buccal bone height, ph: palatal bone height, brl: buccal root lenght, prl: palatal root length. b. Alveolar ridge thickness measurements performed at lines parallel to the HRL and at different vertical levels. bpc: buccal plate cervical at a distance 1 mm from thr tip of the buccal crest, bpm: at the level of the middle of buccal root length (brl), bpa: buccal plate apical at the level of the root apex, ppc: palatal plate cervical at a distance 1mm from the tip of the palatal crest, ppm: palatal plate middle at the level of the middle of palatal root length (prl), ppa: palatal plate apical at the level of the root apex.

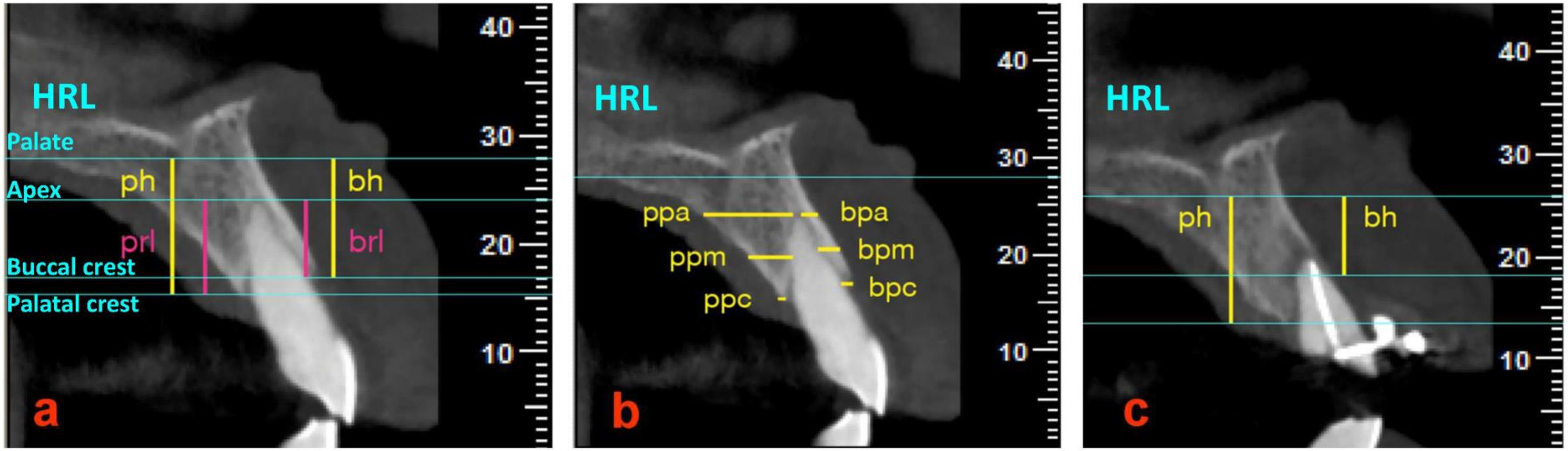


Figure 3. Indicative three dimensional (3D) representation of the alveolar ridge response to tooth extraction using Orthodontic Forced Eruption (OFE). Resorption and loss of the buccal bone are evident and accompanied by augmentation of the palatal and proximal bone (red arrows).

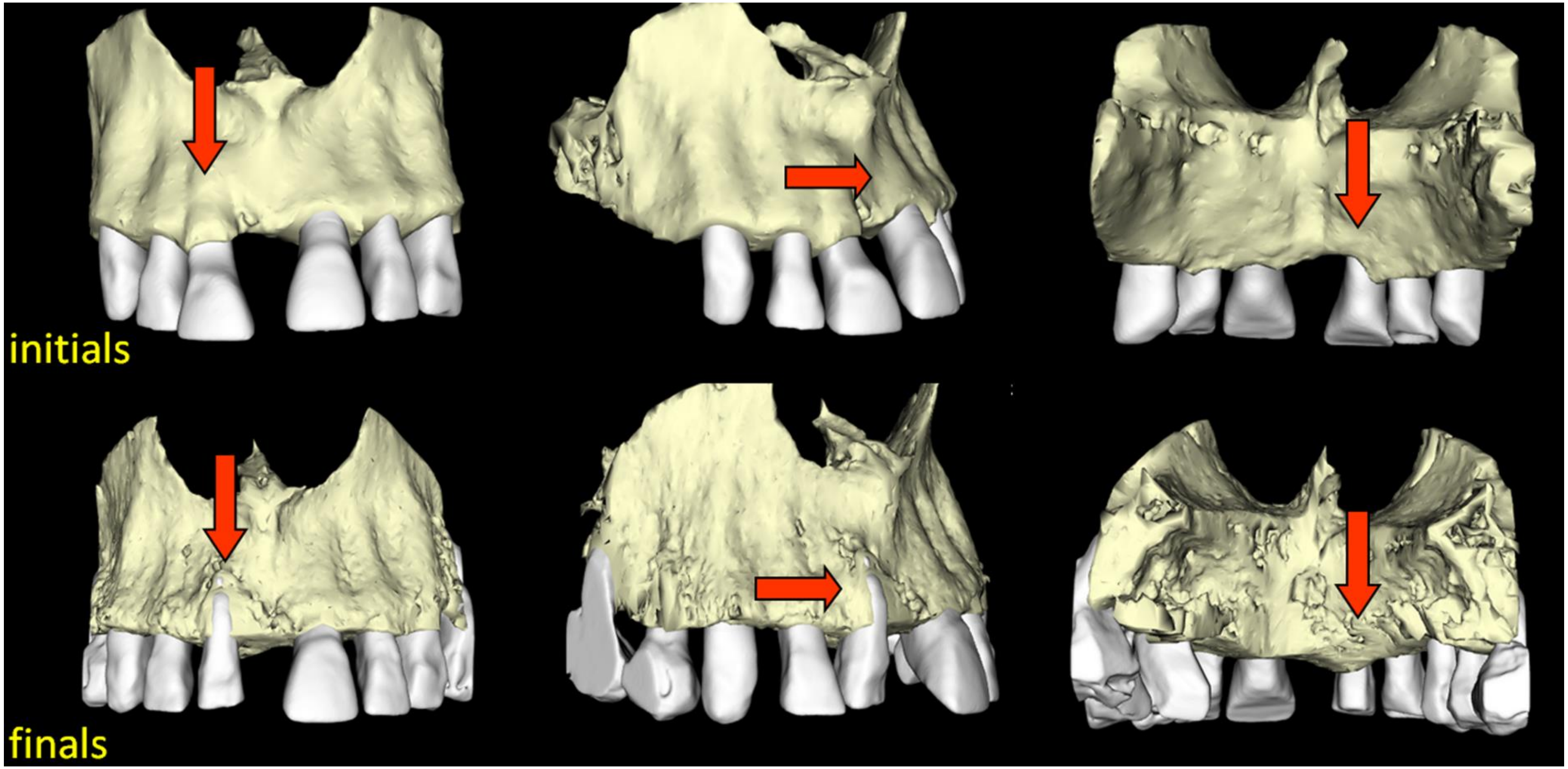
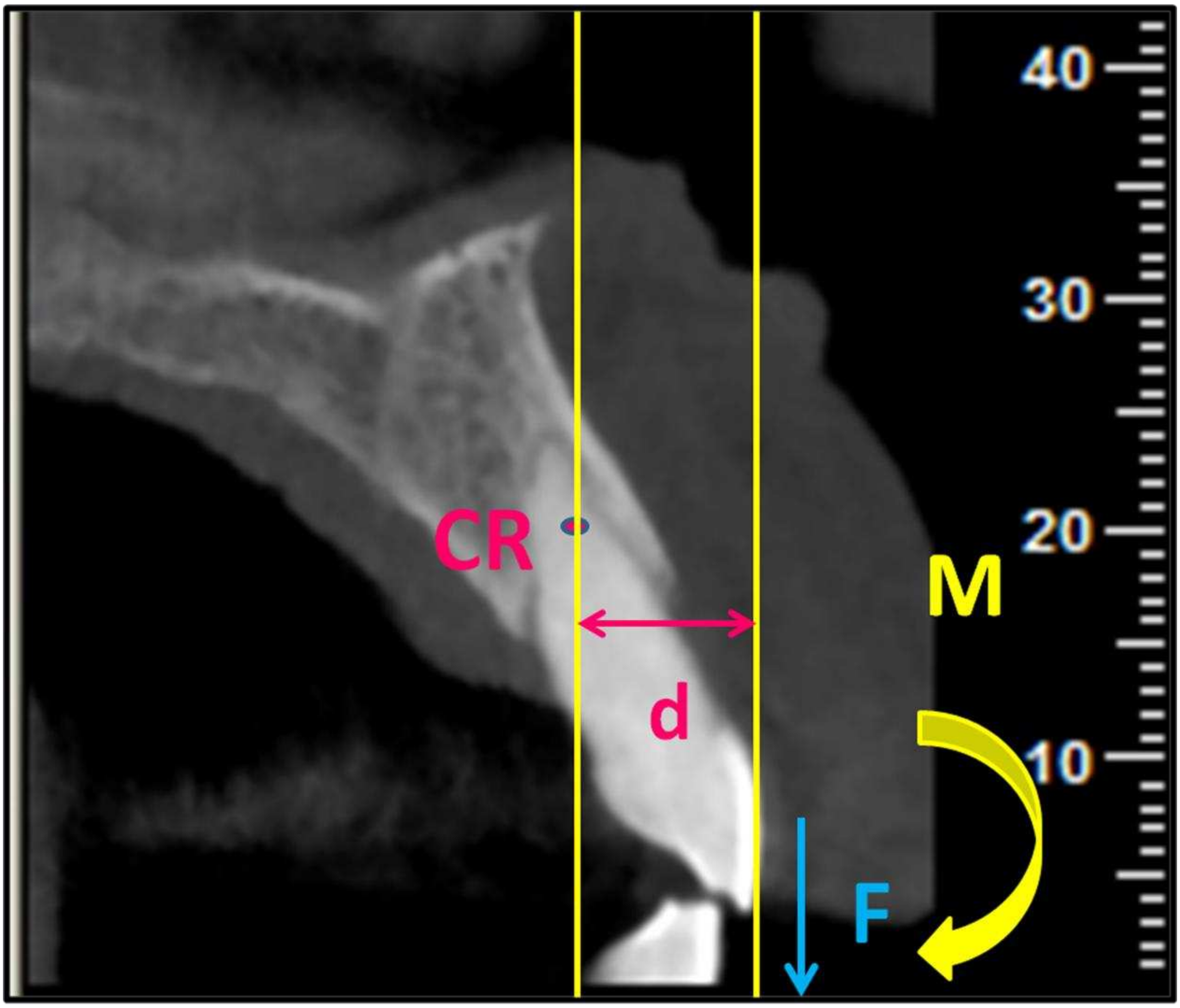


Figure 4. Force vector (F) and moment (M) developed during extraction using Orthodontic Forced Eruption (OFE). Extrusive force (F) delivered from the buccal surface at a distance (d) from the center of resistance (CR) of the tooth generates a clockwise moment (M), where (M) = (F) x (d), which rotates the crown palatally and the root buccally. This biomechanical system delivers pressure to the buccal cortical bone leading to subsequent resorption.



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Tables

Table 1. Initial (T1), final (T2) and difference (T2-T1) of mean values with standard deviations (SD) for alveolar ridge height measurements in the central and interproximal cross-sections of the sockets (N: number of examined sockets, *P*: statistical significance).

	N	Initial (T1)	Final (T2)	T2-T1	95% Confidence Interval (T2-T1)		*P* (T2-T1)
		Mean±SD mm	Mean±SD mm	Mean±SD	Lower bound	Upper bound	
Buccal height (central)	17	10.85±2.48	8.91±2.92	-1.95±1.83	-2.89	-1.01	< 0.001**
Palatal height (central)	17	12.49±2.48	13.80±2.16	1.31±2.41	0.07	2.55	0.039*
Buccal height (interproximal)	17	10.87±1.99	11.10±2.11	0.23±0.93	-0.24	0.70	0.325
Palatal height (interproximal)	17	12.79±1.89	13.42±1.70	0.63±1.59	-0.18	1.44	0.121

*Significant at $P \leq 0.05$

Table 2. Factors affecting bone changes in the buccal and palatal proximal and central sites of the treated sockets estimated with linear regression analysis. β: regression coefficient, CI: confidence intervals, *P*: statistical significance.

		Buccal proximal		**Palatal proximal**		**Buccal center**		**Palatal center**	
Factor	**Category**	**β (95% CI)**	***P***	**β (95% CI)**	***P***	**β (95% CI)**	***P***	**β (95% CI)**	***P***
Tooth	Central								
	Lateral	-0.08 (-1.54 to 1.39)	0.90	-0.83 (-3.50 to 1.84)	0.48	1.52 (-1.45 to 4.49)	0.26	-1.68 (-5.43 to 2.06)	0.31
	Canine	0.14 (-0.65 to 0.93)	0.68	-0.70 (-2.88 to 1.47)	0.46	0.47 (-4.02 to 4.95)	0.81	-1.92 (-5.65 to 1.82)	0.26
Root length buccal		0.03 (-0.26 to 0.31)	0.83	0.37 (-0.39 to 1.14)	0.28	-0.61 (-0.81 to -0.40)	<0.001*	0.75 (-0.29 to 1.80)	0.13
Root length palatal		0.01 (-0.20 to 0.23)	0.88	0.18 (-0.15 to 0.52)	0.23	-0.43 (-0.76 to -0.10)	0.02*	0.43 (-0.15 to 1.01)	0.12
Buccal plate cervical		0.00 (-1.08 to 1.07)	1.00	0.06 (-0.50 to 0.61)	0.81	0.44 (-1.64 to 2.52)	0.62	0.16 (-0.89 to 1.20)	0.73
Buccal plate middle		-0.31 (-1.40 to 0.78)	0.51	-0.56 (-2.11 to 0.99)	0.41	0.74 (-0.66 to 2.13)	0.24	-0.81 (-2.92 to 1.29)	0.38
Buccal plate apical		-0.16 (-0.70 to 0.38)	0.49	0.09 (-0.53 to 0.70)	0.74	0.82 (0.18 to 1.46)	0.02*	-0.25 (-1.33 to 0.83)	0.59
Palatal plate cervical		0.08 (-0.63 to 0.80)	0.78	-0.37 (-2.04 to 1.30)	0.61	0.47 (-2.14 to 3.07)	0.68	0.13 (-2.08 to 2.33)	0.89
Palatal plate middle		-0.01 (-0.62 to 0.59)	0.96	0.37 (-0.26 to 1.01)	0.20	-0.31 (-0.88 to 0.26)	0.24	0.48 (-0.29 to 1.25)	0.18
Palatal plate apical		0.04 (-0.31 to 0.39)	0.79	0.32 (-0.14 to 0.78)	0.14	-0.25 (-0.59 to 0.09)	0.12	0.42 (-0.21 to 1.05)	0.16
Age	Per year	0 (-0.05 to 0.05)	0.92	-0.04 (-0.13 to 0.05)	0.33	0.03 (-0.03 to 0.08)	0.25	-0.08 (-0.23 to 0.08)	0.27

*Significant at $P \leq 0.05$

Table 3. Factors affecting implant placement estimated with linear regression analysis. β: regression coefficient, CI: confidence intervals, *P*: statistical significance.

Factor	**Category**	**β (95% CI)**	***P***
Tooth	Central	Referent	
	Lateral	1.50 (0.70 to 3.23)	0.30
	Canine	0.90 (0.20 to 4.15)	0.89
Root length buccal		0.95 (0.77 to 1.18)	0.66
Root length palatal		1.00 (0.84 to 1.20)	0.97
Buccal plate cervical		1.32 (1.06 to 1.65)	0.01*
Buccal plate middle		3.33 (0.52 to 21.38)	0.21
Buccal plate apical		1.06 (0.49 to 2.31)	0.88
Palatal plate cervical		2.49 (0.34 to 18.01)	0.37
Palatal plate middle		1.03 (0.90 to 1.18)	0.62
Palatal plate apical		0.97 (0.87 to 1.08)	0.55
Age	Per year	1.01 (0.98 to 1.04)	0.61

*Significant at $P \leq 0.05$

Table 4. Implant Stability Quotient (ISQ) values at different time points.

	T1 Implant insertion	T2 Provisionalisation	T3 Final Prosthesis (6 months after T1)	T1 vs T2 (*P*)	T2 vs T3 (*P*)	T1 vs T3 (*P*)
ISQ measurements (mean ± SD)	71±2.80	69.95±3.00	74.45±2.97	0.33	0.002	0.02

*Significant at $P \leq 0.05$

Supplementary material

Supplementary Table 1. Patient initials, gender, age, total number and sites of teeth extracted with Orthodontic Forced Eruption (OFE), reasons of tooth loss, numbers of inserted implants, sites eligible for immediate implant placement and orthodontic treatment duration for each patient.

Subjects initials	Gender	Age (years)	Number of teeth extracted with OFE (17)	Sites of extracted teeth	Etiology for tooth loss	Number of implants (11)	Sites of placed implants	Orthodontic treatment duration (months)
		Mean ± SD 43.14 ± 16.23						Mean ± SD 10.86 ± 4.6
SA	M	20	1	1.1	Trauma (non treatable crown fracture)	1	1.1	16
MK	F	42	1	2.2	Periodontitis	1	2.2	7
KC	F	48	4	1.2 / 1.1 / 2.1 / 2.2	Periodontitis	4	1.2 1.1 2.1 2.2	17
SN	F	61	4	1.3 / 1.2 / 2.1 / 2.2	Periodontitis	2	1.3 2.2	13
MC	F	65	1	1.1	Periodontitis	1	1.1	8
VM	F	30	2	1.1 2.1	Trauma (non treatable crown fracture)	0	0	10
BG	F	36	4	1.2 / 1.1 / 2.2 / 2.3	Periodontitis	2	1.2 2.2	5

Supplementary Table 2. Baseline means and standard deviations (SD) of the buccal and palatal root length of teeth extracted with Orthodontic Forced Eruption (OFE) and the alveolar plate thickness measured at the cervical, mid-root and apical level in the initial CBCT sagittal reconstructions. N: number of examined sockets.

	N	Mean ± SD (mm)
Buccal root length (brl)	17	5.26 ± 2.05
Palatal root length (prl)	17	6.91 ± 2.24
Buccal plate cervical (bpc)	17	1.06 ± 0.58
Buccal plate middle (bpm)	17	1.24 ± 0.85
Buccal plate apical (bpa)	17	1.34 ± 0.60
Palatal plate cervical (ppc)	17	1.61 ± 0.56
Palatal plate middle (ppm)	17	3.50 ± 1.44
Palatal plate apical (ppa)	17	6.15 ± 2.72

Supplementary Table 3. Intraclass Correlation Coefficient (ICC) for assessment of reliability of measurement with lower and upper limits. Paired t-test used for estimating systematic errors with the mean of the difference between repeated measurements for each variable and *P* values. Negative sign of the mean difference between repeated measurements depicts that the means of the second measurement were greater than the means of the first measurement. ICC values greater than 0.80 indicate great reliability and *P* values >0.05 indicate that the differences between the first and the second measurement were not significant.

Variable (mm)	ICC	Lower limit	Upper limit	Paired t-test Mean (mm)	*P*
root length buccal	0.999	0.997	1.000	0.01529	0.532
root length palatal	0.999	0.996	1.000	0.00176	0.953
B plate cervical	0.996	0.988	0.998	0.00882	0.521
B plate middle	0.996	0.990	0.999	-0.1941	0.290
B plate apical	0.989	0.971	0.996	-0.00824	0.711
P plate cervical	0.994	0.983	0.998	0.00941	0.567
P plate middle	0.998	0.993	0.999	0.01529	0.546
P plate apical	0.997	0.992	0.999	-0.02471	0.649
initial buccal height	0.997	0.992	0.999	-0.01294	0.750
final buccal height	0.996	0.989	0.999	0.00765	0.876
initial palatal height	0.996	0.990	0.999	-0.01353	0.758
final palatal height	0.992	0.978	0.997	-0.02471	0.654